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MEMORANDUM REPORT ARBRL-MR-03332

EFFECTS OF ATMOSPHERIC AIR ON PROJECTILE ACCELERATION IN THE RAIL GUN

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February 1984

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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4. TITLE (and Subtitle) EFFECTS OF ATMOSPHERIC AIR ON PROJECTILE ACCELERATION IN THE RAIL GUN		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John D. Powell		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory, ARDC ATTN: DRSMC-BLB(A) Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS RDT&E 1L162603AH18
11. CONTROLLING OFFICE NAME AND ADDRESS US Army AMCCOM, ARDC Ballistic Research Laboratory, ATTN: DRSMC-BLA-S(A) Aberdeen Proving Ground, MD 21005		12. REPORT DATE February 1984 13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Rail gun
Electromagnetic propulsion
Electric gun
Hypervelocity acceleration
Atmospheric drag

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (idk)

The manner in which projectile velocity in a rail gun is limited by the presence of atmospheric air in the gun tube is studied. In particular, we solve the equation of motion for the acceleration of the armature and projectile, accounting for both the decelerating force exerted by the atmosphere and the time decay of the current profile. From the solution, a characteristic time is derived which indicates quantitatively when the effect of the atmosphere can be expected to be significant. Results of the calculation (continued)

are then compared qualitatively with results from two recent experiments, one in which atmospheric effects are nearly negligible and one in which they are not.

I. INTRODUCTION

In recent years rail guns have been used to accelerate macroscopic projectiles to velocities as high as several km/s.[1,2] Some interesting results obtained in a recent experiment, to be discussed presently, have caused speculation that atmospheric air in the gun tube may significantly limit projectile velocity. In this communication we wish to determine under what conditions such an effect might be important.

II. CALCULATIONS

The principle on which the rail gun operates is shown schematically in Fig. 1. Current is conducted along the rails in the direction indicated and from the lower to upper rail through an armature which may be either solid or gaseous. The resulting magnetic field then interacts with the armature current, giving rise to a force which accelerates the armature and projectile (shaded area) down the gun tube. Unless the region of the gun tube in front of the projectile is evacuated prior to acceleration, the projectile motion will produce a shock wave that exerts a retarding pressure P_S on the accelerating system. We will now solve the equations of motion of the armature and projectile to determine the effect of P_S. It is assumed that the current varies exponentially according to the relation

$$i = i_0 \, e^{-t/t_0}, \tag{1}$$

since the current in our rail gun, which has inductive energy storage, has been successfully fit to such a profile. Results should not be affected qualitatively for other types of variation. In the case of a plasma armature it is also assumed that the entire system (armature and projectile) is accelerated at the same rate.

Under these conditions the appropriate equation of motion becomes

$$m \frac{dv}{dt} = \frac{1}{2} L' \, i_0^2 \, e^{-2t/t_0} - P_S \, A \tag{2}$$

where m is the total mass of the armature and projectile, L' the inductance per unit length of the rails, and A the cross-sectional area of the gun tube. Now, for typical rail guns and acceleration times of interest, the first term on the right-hand side of Eq. (2) is large compared to the second except when P_S is much greater than atmospheric pressure. Consequently, we can approximate P_S by a strong-shock approximation,[3] namely,

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[1] *S.C. Rashleigh and R.A. Marshall, J. Appl. Phys. 49, 2540 (1978).*

[2] *R.S. Hawke, R.L. Brooks, F.J. Deadrick, J.K. Scudder, C.M. Fowler, R.S. Caird, and D.R. Peterson, IEEE Trans. Magn. MAG-18, 821 (1982).*

[3] *Y.B. Zel'dovich and Y.P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Academic, New York, 1966, Chap. I.*

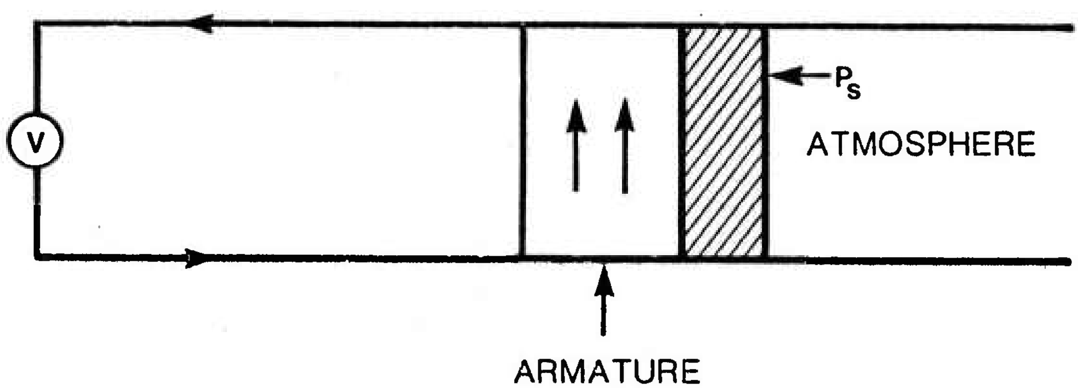

Figure 1. Schematic Drawing of Rail Gun.

$$P_S \simeq \frac{1+\gamma}{2}\, \rho_0\, v^2 \tag{3}$$

where γ is the ratio of the specific heat at constant pressure to that at constant volume and where ρ_0 is atmospheric density, i.e., 1.29 kg/m^3.

Substituting Eq. (3) into Eq. (2) we obtain a nonlinear differential equation for the velocity v. The equation can be linearized, however, by the transformation[4]

$$v = \frac{2m}{(1+\gamma)\rho_0\, A\, u} \frac{du}{dt} \quad , \tag{4}$$

and further simplified by letting

$$z = z_0\, e^{-t/t_0} \tag{5}$$

where

$$z_0 = \frac{[L' i_0^2\, (1+\gamma)\, \rho_0\, A\, t_0^2]^{1/2}}{2m} \quad . \tag{6}$$

Physically, z_0 is a measure of the importance of the air in gun tube, its decelerating effect increasing with increasing z_0. We obtain after some algebra

$$z \frac{d^2u}{dz^2} + \frac{du}{dz} - z\, u = 0 \quad , \tag{7}$$

a modified Bessel equation. The solution of Eq. (7) consists of a linear combination of the functions[5] $I_0(z)$ and $K_0(z)$. Using this result for u in Eq. (4), applying the initial condition $v(t=0) = 0$, and using formulas[5] for the derivatives of the Bessel functions, we find for the time-dependent velocity

$$v = v_0(z) \left\{ \frac{2z}{z_0^2 - z^2} \left[\frac{K_1(z)\, I_1(z_0) - K_1(z_0)\, I_1(z)}{K_0(z)\, I_1(z_0) + K_1(z_0)\, I_0(z)} \right] \right\} \quad . \tag{8}$$

Here v_0 is the solution of the problem in the absence of air ($\rho_0 = 0$), namely,

$$v_0 = \frac{L'\, i_0^2\, t_0}{4m} \left(1 - z^2/z_0^2\right) \quad . \tag{9}$$

To determine when the effect of the air first becomes important, we can (arbitrarily) set $v/v_0 = 0.95$ and solve Eq. (8) for z as a function of z_0.

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[4] *B.M. Murphy, Ordinary Differential Equations and Their Solutions, van Nostrand, New York, 1960, Chap. A1.*

[5] *Handbook of Mathematical Functions, edited by M. Abramowitz and I. Stegun, National Bureau of Standards, Washington, DC, 1964, Chap. 9.*

From the resulting value of z, denoted by z_c, the "characteristic time" follows from the relation

$$t_c = t_0 \ln (z_0/z_c) \quad . \tag{10}$$

For acceleration times less than this value, the effects of the air are negligible, while for larger times they are not. In Fig. 2 is plotted z_c vs. z_0 from a numerical solution of Eq. (8) with $v/v_0 = 0.95$. For values of z_0 somewhat above unity, the result is linear and given by the relation

$$z_c = z_0 - \sqrt{0.15} \quad . \tag{11}$$

The validity of Eq. (11) can be demonstrated from asymptotic expansions[5] of the Bessel functions. Since z_c/z_0 increases monotonically with z_0, the characteristic time t_c decreases with z_0. Thus, the presence of the air is likely to be important for large values of z_0 or under acceleration conditions corresponding to high currents, small masses, and long time constants.

We can also determine from Eq. (8) the time at which the maximum velocity occurs. This value is obtained when the term in square brackets in Eq. (8) is unity as can be shown by setting the derivative equal to zero in Eq. (12) and comparing the resulting expression for v with that in Eq. (8). Again, we solve numerically for z as a function of z_0 and denote the values by z_m. Results are plotted in Fig. 2. For z_0 sufficiently large, z_m varies nearly linearly with z_0 and satisfies the transcendental relation

$$z_m = z_0 - \frac{\ln (4\, z_m)}{2} \quad , \tag{12}$$

as can be shown from the appropriate asymptotic expansions. The time at which the maximum velocity occurs, of course, is obtained from z_m via the analog to Eq. (10).

To demonstrate further the results of Eq. (8) we have plotted v and v_0 as a function of t for data corresponding roughly to two recent experiments.[6] Each was carried out with the same rail gun for which appropriate parameters were $A = 1.61\ \text{cm}^2$, $i_0 = 150$ kA, and $t_0 = 752\ \mu s$; the inductance per unit length L' was assumed to be 0.42 μH/m and the parameter γ was given by 1.4, which is appropriate for air. In the first experiment, only a plasma arc was accelerated, whereas in the second both the arc and a 2.5 g projectile were employed. The

[6] *K.A. Jamison and H.S. Burden (private communication).*

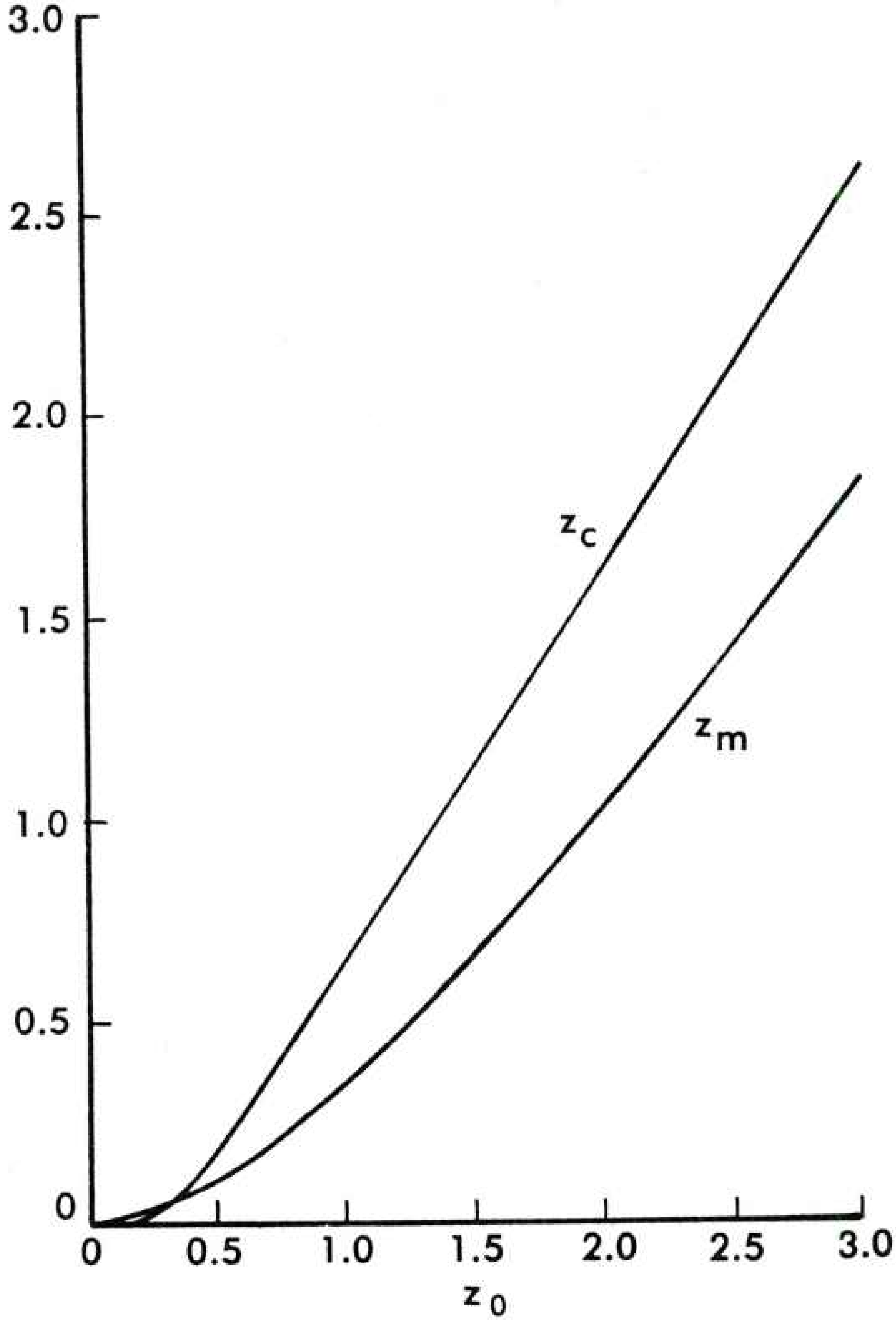

Figure 2. The parameters z_c and z_m, used to determine the characteristic time and the time of maximum velocity, as a function of z_0. [See Eq. (6).]

mass of the arc was not known but we assumed a value of 0.1 g, as has been done in previous work.[7,8] Corresponding values of z_0 for the two experiments were 8.2 and 0.31, respectively.

Results for the two cases are shown in Fig. 3. The time scale is in milliseconds, while the velocity scale is in km/s for Case 1 (arc only, no projectile) and hundreds of m/s for Case 2 (arc and projectile). In both instances results are plotted only for the approximate time during which the projectile or armature was in the 1m-long gun tube.

As is evident from the figure, the air has little effect upon the acceleration of the finite-sized projectile since v_0 differs only slightly from v during the course of acceleration. In fact, the characteristic time for this case, calculated in the manner described previously, is 1.25 ms and the two velocities do not differ by more than 5% for times less than t_c. It should be noted that the velocity reaches its maximum value (~ 631 m/s) around 1.45 ms and is limited primarily by the time decay of the current. The atmosphere has little effect.

For the case in which only the arc is accelerated, we see that the air exerts a very significant effect upon the acceleration process. The characteristic time for this case is only 0.04 ms and the difference between v and v_0 grows rapidly thereafter. The maximum velocity reached is about 3.4 km/s and is attained at t = 0.17 ms. In this case the velocity is limited primarily by the effect of the air since the current decays little during the time of acceleration.

Results of the calculation are in good qualitative agreement with the experiments in question. For the 2.5 g projectile, the velocity increased steadily over the first 37 cm of the gun tube (the location of the last detector). When only the arc was accelerated, however, the velocity was found to rapidly approach about 3 km/s and remain nearly constant thereafter, behavior consistent with the results of Fig. 3. Specifically, a distance vs. time curve plotted at the location of the four detectors (at 7, 17, 27, and 37 cm from the breech end of the gun tube) produced nearly a straight line. It might appear surprising that the maximum velocity of the arc is predicted reasonably accurately since the arc mass was only crudely estimated. For constant currents, however, which nearly apply to this case, v_{max} becomes independent of m and is given by

$$v_{max} = \left(\frac{L' \, i_0^2}{(1+\gamma)\rho_0 A} \right)^{1/2} . \tag{13}$$

To summarize, the nearly constant value of the velocity observed in the experiment when only the arc was accelerated suggested to us that atmospheric drag might be significant in some rail-gun experiments. Results of the calculation have suggested that such an effect is indeed important at high velocities

[7] *I.R. McNab, J. Appl. Phys.* *51*, *2549 (1980).*

[8] *J.D. Powell and J.H. Batteh, J. Appl. Phys.* *52*, *2717 (1981).*

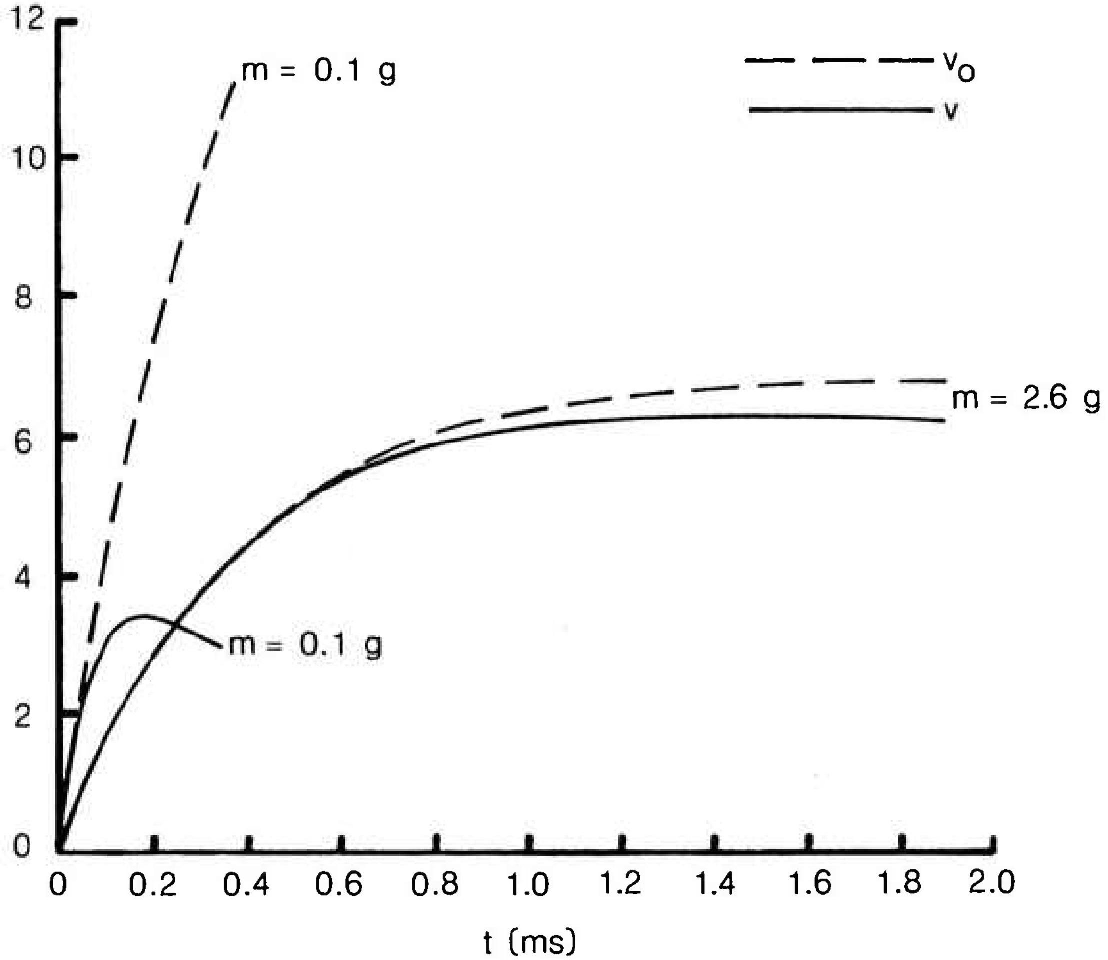

Figure 3. Arc and projectile velocity, with and without atmospheric effects, for two different cases. For m = 0.1g (no projectile), the vertical scale is in km/s; for m = 2.6g (arc and projectile present), the vertical scale is in hundreds of m/s.

and is apparently capable of explaining these experimental results. Precise conditions under which air exerts an appreciable decelerating force on the projectile can be determined for any experiment by calculating z_0 for the case at hand and using Fig. 2 to obtain the corresponding characteristic time.

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